# Evolution, structure and petroleum geology of the German Molasse Basin

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## ABSTRACT

The German Molasse Basin is a 300 km long segment of the of North-Alpine foredeep. In cross section, it is a composite wedge, up to 120 km wide and 0.3 to 6 km thick. Its basin fill consists of late Eocene to middle Miocene alternating marine and non-marine Alpine-derived clastics which were deposited during an estimated trans-basinal convergence of 250 to 400 km. Two successive and superposed megasequences reflect pre-extended lithosphere with a rigidity of $0.6 \cdot 10^{23}$ Nm. The older megasequence (42 to 20 Ma) coincides with the collision of the Adriatic and Penninic continental fragments with an edge-loaded European plate. The younger megasequence (20 to 8.5 Ma) shows 170 km or less of convergence and the weak and line-loaded flexure of the rising Alpine mountains. Deformation within the present Molasse Basin is dated at 12 Ma or possibly even as little as 6 to 2 Ma.

Developed oil and gas reserves amount to some $10 \cdot 10^6$ t ($80 \cdot 10^6$ bbl) of petroleum liquids and $21 \cdot 109$ $m^3$ of gas (735 BCF). These are contained in 59 mostly small oil and gas fields which are sourced and trapped within and below the undeformed Molasse wedge. Untested deep-gas potential exists in footwall imbrications near the Alpine front.

## INTRODUCTION

The German Molasse Basin is a 300 km wide segment of the north-Alpine foredeep between the Rhine and Salzach rivers (Lemcke, 1988; Schwerd and Unger, 1981). This segment has achieved some geological coherence by a common history of mapping and petroleum exploration, manifested in more than 600 exploration and production wells, in 45 oil and gas fields, and in an estimated 5000 km of reflection seismic profiles (Lemcke, 1988). Geologically, it forms a composite wedge-shaped clastic prism which is 30 to 120 km wide and 0.3 to 6 km thick. Its age ranges between Priabonian (42 Ma) and Tortonian (8 Ma) times, and it involves a tectonic convergence of 250 to 400 km.

Our paper summarizes available geological data, describes accepted and new geodynamic

ROEDER, D. & BACHMANN, G., 1996. — Evolution, structure and petroleum geology of the German Molasse Basin. *In*: ZIEGLER, P. A. & HORVÁTH, F. (eds), Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands. *Mém. Mus. natn. Hist. nat.*, **170**: 263-284 + Enclosures 1-4. Paris ISBN: 2-85653-507-0.

*This article includes 4 enclosures on 1 folded sheet.*

interpretations, and speculates about some of the basin-forming mechanisms. Available data is consistent with the consensus of compressional tectonics within the European foreland during the Alpine collision (Ziegler, 1987, 1990; Bachmann et al., 1987). However, available data also suggests flexural response, high strain rates, and high bulk strain during the basin evolution, aspects with are in part contradictory or seemingly inconsistent.

## SETTING AND GEOLOGICAL UNITS

The basin fill is a depositional body affected by tectonic deformation and erosion. It underlies the lowlands between the Alps and the Danube river (Fig. 1). To the south, the undeformed main part or Foreland Molasse is in contact with the deformed part or Folded Molasse. South of a frontal triangle zone, the Folded Molasse is an imbricate stack of up to four thrust sheets or detached folds with 1 to 5 km of estimated individual thrust transport. Typical surface features of the thrust sheets are tight north-vergent, doubly plunging synclines with steep limbs.

South of a structural contact, stratigraphically older units form three stacked North-Alpine belts, the Helveticum, the Rheno-Danubian flysch, and higher thrust systems grouped in the present paper as Austro-Alpine. Transport at the tectonic contacts between these units is polyphase and of plate-tectonic magnitude. The transport components of Tertiary age vary between 10 and 100 km. The poorly known structural style of post-stacking compression involves tight or open and duplex-type folding near the surface and presumably north-vergent imbrication at depth.

The base of the Molasse body corresponds to a regional unconformity which is onlapped by transgressive sands, shelf carbonates and dominant foredeep clastics. This unconformity truncates Mesozoic shelf sediments deposited in a passive-

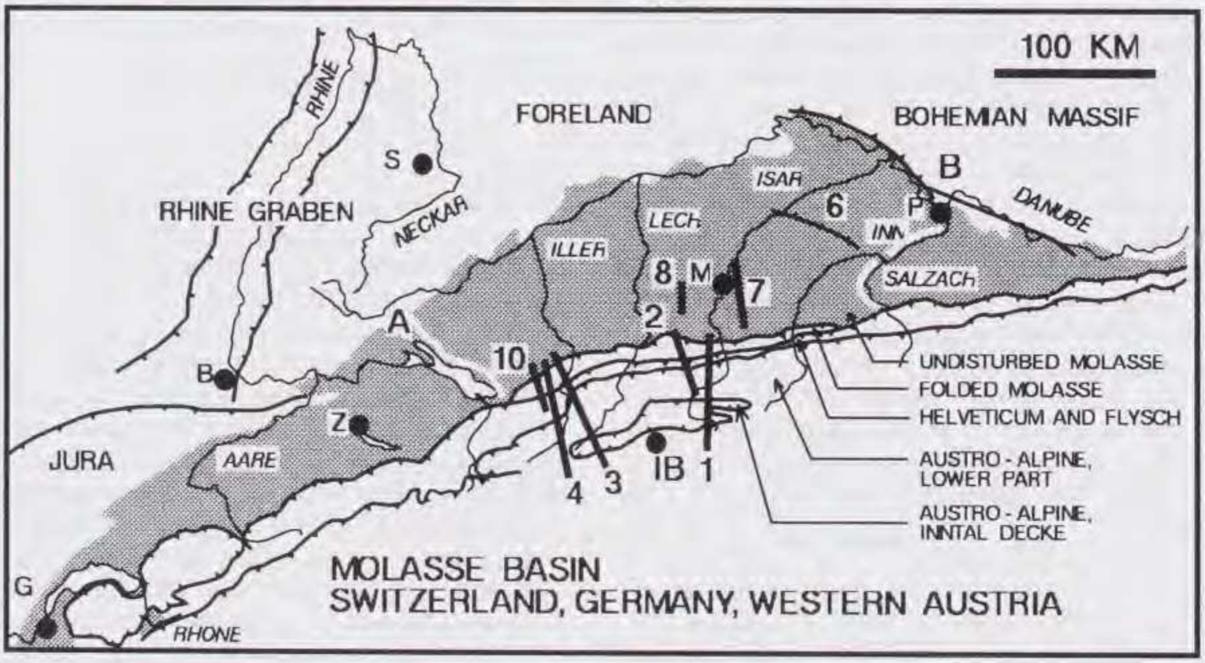


FIG. 1. Location map of north-Alpine Molasse Basin, redrawn afteBachmann and Müller (1991). Shaded: area underlain by foredeep sediments at the surface. White lines marked A and B: limits of the German segment of the Molasse Basin. Black sticks with numbers: cross-sections shown in present paper: 1, 2, 3, 4 : cross-sections on Encls. 1 and 2. 6: Landshut-Neuötting high. 7: basin cross-section given in Fig 7. 8: seismic profile Fig 8. Black dots with letters are cities: Stuttgart, Passau, Munich, Innsbruck, Zürich, Basel, Geneva.

extensional continental margin basin of Jurassic to Late Cretaceous age; their cumulative thickness increases southward from about 1 to 4 km. The structure of this former continental margin is polyphase and extensional; it shows pre-Alpine highs, rifts, and inverted basins. It is also affected by brittle extensional faulting of Tertiary age providing most of the productive hydrocarbon traps.

The crust beneath this sedimentary prism, its original southward extent, and possibly, its southward thinning, are partly defined by a gently south-dipping seismic Moho event. An abrupt southward rise of the Moho is observed near the South-Alpine Insubric line, located about 120 km south of the northern Alpine front. Perhaps this rise signals the southern edge of the foreland crust (see Ziegler et al., this volume).

## STRATIGRAPHY AND BASIN EVOLUTION

Within the German Molasse Basin, Permo-Carboniferous to Tertiary sediments and subdividing unconformities record four evolutionary stages, from bottom to top, a rift-fill series, an epicontinental basin series, a passive-margin series and an Alpine foredeep series.

Late Palaeozoic continental fill of transtensional troughs overlays a Variscan basement which is coherent with the European crust at a cratonic thickness near 30 km (Ansorge et al., 1992). Several of the late Variscan troughs have been tentatively mapped, based on reflection-seismic data and on a handful of deep wells (Lemcke, 1988). Their fill can be more than 1 km thick and shows the ENE and WNW trends of the Variscan wrench-fault pattern in W-Europe and NW-Africa (Arthaud and Matte, 1977; Ziegler, 1990).

The basin floor is formed by a 1 km thick pair of shallow-marine sedimentary series. A Triassic to Middle Jurassic north-facing epicontinental basin series onlaps the basement from NW to SE and thins southward. It is overlain by a Middle Jurassic to Cretaceous passive-extensional-margin series, which faces to the south and thickens southeastwards. Isopach maps (Bachmann et al., 1987) show a regional element of southeastward thickening at rates of 10 m or less per km, and more local elements of crustal tectonics.

Molasse subcrop maps (Lemcke, 1988; Bachmann et al., 1987) show a persistence of the Mesozoic regional element in the form of a gentle bevelling toward the northwest. The thickest and most complete south parts of the basin-floor series now constitute the Alpine thrust sheets south of the present Molasse Basin.

An extensional event of Jurassic age records the shift from the epicontinental setting to the passive-margin setting. This event is important for structures and as a generator of petroleum source-rocks. It is recorded within the Alpine thrust sheets, but apparently it did not directly affect the German Molasse Basin.

Late Cretaceous to Paleogene strike-slip faulting generated a NW-trending block mosaic in the Mesozoic double sequence, in particular the Landshut-Neuötting High and the Bohemian Massif. These movements are related to the change in the Europe-Africa plate vector from southeasterly to northeasterly at 92 Ma (Dewey et al., 1989), and to compressional tectonism in the Alpine foreland (Ziegler, 1987, 1990). In the German Molasse Basin, its effects include extensive truncation of the Mesozoic sediments.

The fourth sediment sequence of the German Molasse Basin is a 0.1 to 5 km thick Tertiary clastic foredeep fill of Alpine and limited local provenance. Its relationship to the Alpine collision is clearly evident in its northwestward onlap and in its facies evolution from marine and turbiditic sandstones to non-marine clastics. It is also evident in the extensional tectonics of its substratum and, finally, in the trans-Alpine plate convergence. Since the late Eocene, subduction beneath the Adriatic plate may have begun to involve the south edge of the European continental crust. Flexural loading of the crust entailed truncation of the north parts of the Mesozoic shelf, and subsidence and marine sedimentation in the south parts. Most of the earliest Molasse sediments were probably buried beneath advancing thrust sheets. The younger Molasse formations were derived from emerging Alpine terranes and by cannibalizing the more southerly basin fill.

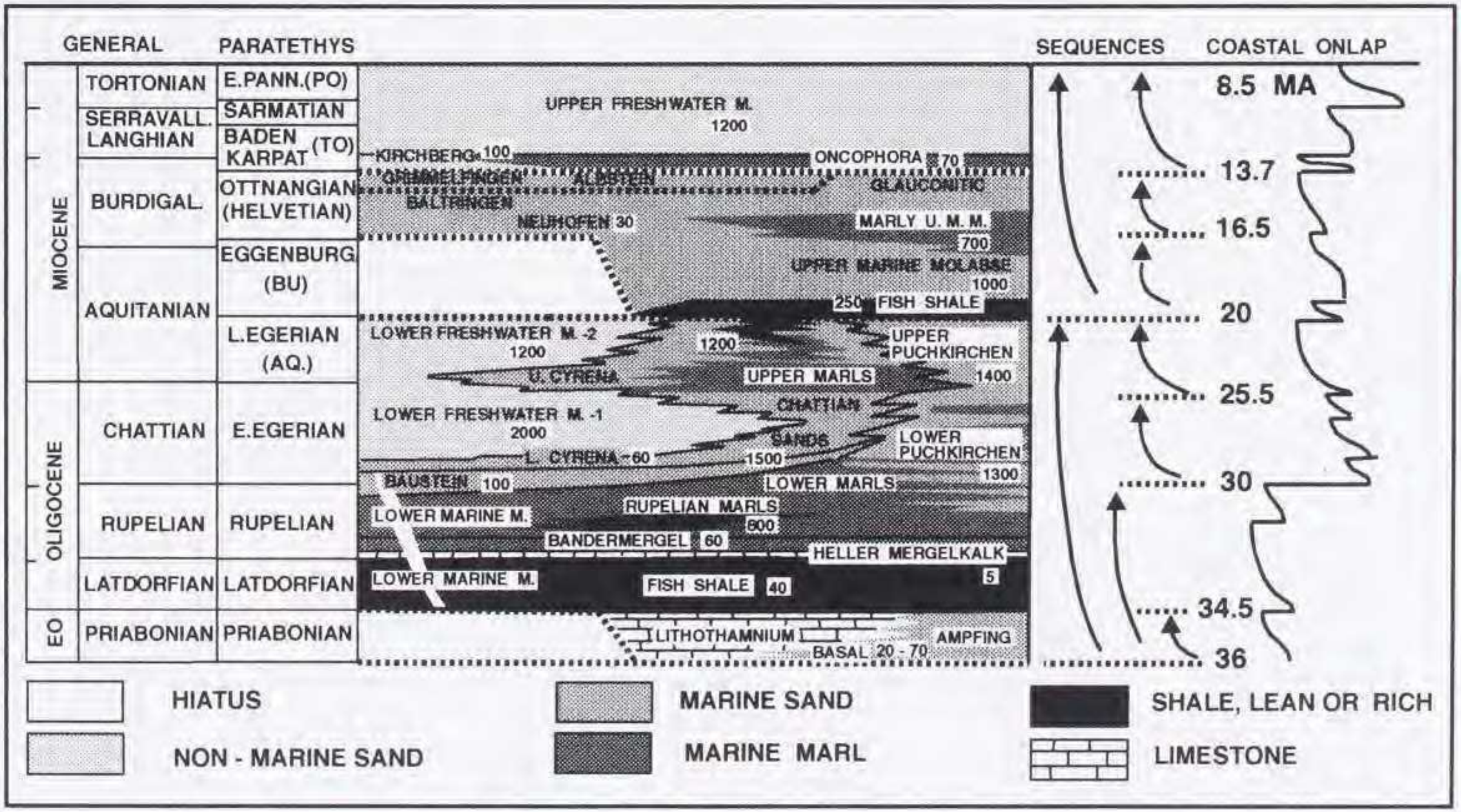


FIG. 2. Stratigraphic table of the German Molasse Basin, redrawn after Bachmann and Müller (1991), with shade patterns explained in a legend. On right, the transgressive-regressive sequences (vertical arrows) and their correlation with the coastal onlap curve (Vail et al., 1988). Chronostratigraphy, on left, after Steininger et al. (1985) and Fahlbusch (1981). Old, now obsolete stages in brackets: (AQ): Aquitanian, (BU): Burdigalian, (Helvetian); (TO) Tortonian; (PO) Pontian. Lithostratigraphy (central panel) modified from Lemcke (1988). Numbers in the centre field refer to average thicknesses in meters. Numbers to the right are geological ages.

## MOLASSE DEPOSITIONAL SEQUENCES

In the German Molasse Basin, a system of four lithostratigraphic units can be recognized on the basis of biostratigraphy, mapping, and well results (Hagn and Hölzl, 1952; Ganss and Schmidt-Thomé, 1955; Hagn, 1960; Breyer, 1960). This system is still in use and includes the Lower Marine Molasse, Lower Freshwater Molasse, Upper Marine Molasse, and Upper Freshwater Molasse. Sequence stratigraphy (Haq et al., 1988), useful for dealing with high-resolution seismic data, sedimentology, and geodynamic concepts, is also used in the Molasse Basin (Lemcke, 1988; Bachmann and Müller, 1991; Jin, 1995).

Figure 2 shows a tentative correlation chart between the lithostratigraphic Molasse units and their sequence stratigraphic interpretation (Bachmann and Müller, 1991). It is similar to an east-westerly trending strike section of the German segment, but it shows neither the basal onlap geometry nor the lithostratigraphy of the Folded Molasse province. The chart shows a westward increase in non-marine facies and in non-deposition. It also shows the Molasse series divided into two major transgressive and regressive sequences.

Figure 3, keyed to the sediment bodies shown in Fig. 2, shows the northwesterly prograde pattern of onlap at the base of the Molasse. The onlap pattern shown is interpreted from well control (Bachmann et al., 1987), and it is affected not only by relative sea-level changes, but also by a regional element of elastic load flexure, as well as by local crustal tectonics.

A smoothened abstraction of the basal Molasse onlap pattern and the ages of its elements is shown in Figure 4 as dated lines or isochrons of zero deposition during the onlap. The generalized onlap pattern suggests a finite onlap rate of 0.5 $cma^{-1}$, which is in the same order as, and less than, the tectonic convergence rate. The geometry of the basin fill is further shown in Figures 5 and 6. The following description of the stratigraphy refers to these maps.

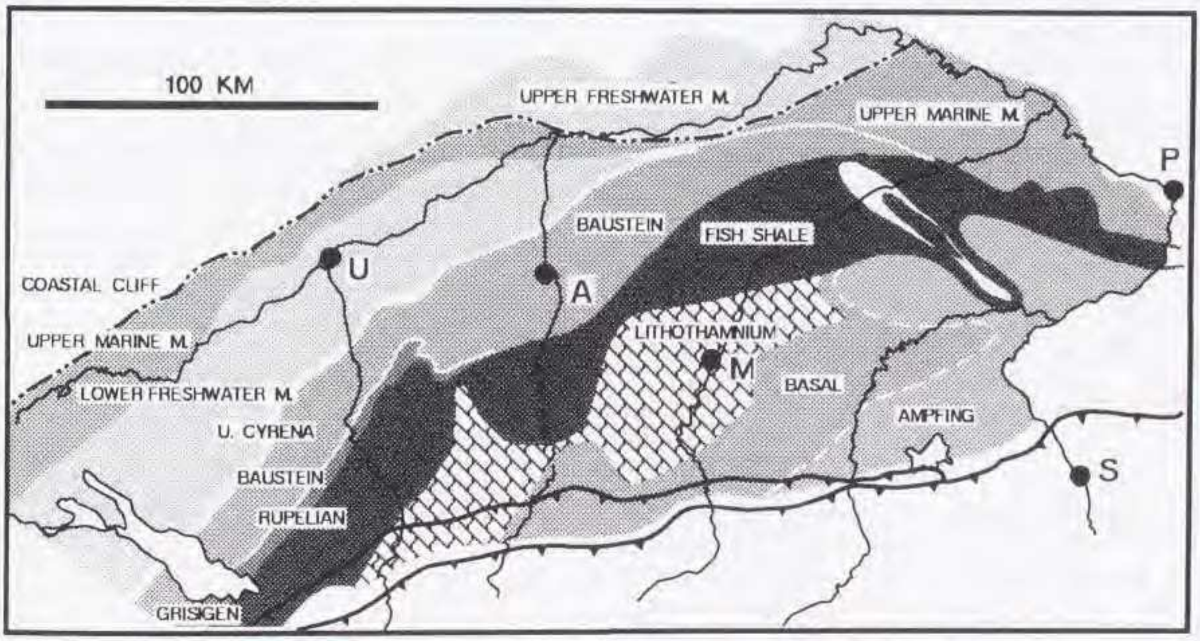


FIG. 3. Onlap map of German Molasse Basin, redrawn after Bachmann and Müller (1991). Shade patterns are geological formations, explained in legend to Fig. 2. Dash-dot-dotted line: coastal cliff of late Burdigalian age (14 Ma) in Jurassic limestones. Dots with letters: Ulm, Augsburg, München, Passau, Salzburg.

## Older Molasse Megasequence

This sequence, of Priabonian (42 Ma) through lower Aquitanian (Egerian) (20 Ma) age, includes the Flysch-Molasse transition beds, the Lower Marine Molasse, and the Lower Freshwater Molasse. Late Eocene, locally derived transgressive sands, onlap the Paleocene unconformity and grade upwards into Lithothamnium limestones forming a broad platform (Figs. 2 and 3). Farther downdip, continuous sedimentation and a transition into Helvetic or Ultrahelvetic flysch units have been established stratigraphically, for example in the Hindelang-1 well (Huber and Schwerd, 1995). Everywhere in outcrop at the south edge of the Folded Molasse, evidence for this continuity is disrupted by late Miocene-age thrust tectonics and brittle strike slip (Schmidt-Thomé, 1962; Schwerd, 1983; Doben and Frank, 1983).

Rupelian and Latdorfian fully marine shales, including the organic-rich Fisch Schiefer, Mergelkalk, Bändermergel, Rupelian Marls, and Deutenhausen beds, document a generally transgressive series, in which the regressive early Chattian (30 Ma) coarse-clastic Baustein sands and conglomerates mark the transition into the Lower Freshwater Molasse.

Conglomerates, sandstones, and sandy shales of the Lower Freshwater Molasse thicken to 4 km in the Subalpine Molasse of Central Switzerland (Trümpy, 1980). An abundance of sedimentological details demonstrates changes in sea level, tectonic pulses, topographic changes and drainage slow-downs in the Alpine sediment source area (Lemcke, 1988; Müller, 1991; Jin, 1995).

## Younger Molasse Megasequence

This sequence spans late Aquitanian (20 Ma) to late Tortonian (8.5 Ma) times and includes the Upper Marine Molasse, the Freshwater-Brackish Molasse, and the Upper Freshwater Molasse. The base of this sequence corresponds to an unconformity which toward the east disappears in marine shales of Chattian age (Egerian, 21 to 20 Ma) or in the marly Upper Marine Molasse of Eggenburgian age (20 to 18 Ma, Fig. 2). This unconformity can be related to strong basinal axial currents and to a narrowing of the basin as a consequence of nappe emplacement (P.A. Ziegler, personal communication). Regional structure data (Doben, 1981; Lemcke, 1988) also suggest a change in the parameters of the elastic foreland deflection at this unconformity, as induced by the load of the advancing Alpine body.

This Miocene megasequence onlaps northward through the Miocene with shallow-marine sands and silts. Beyond the present northern basin edge, a coast line with lithophagous traces of Ottnangian age (Helvetian, 18 to 15 Ma) represents an instant in transgressive onlap over Jurassic limestones. During the younger parts of this megasequence, relative sea level dropped and nonmarine sedimentation continued for another 7 or 8 Ma in the Upper Freshwater Molasse. Sedimentation ended at about 8 Ma and was followed by fluviatile erosion.

The total volume preserved of the younger megasequence (Fig. 6) is estimated at only about half of the preserved older megasequence. In part, this reflects the post-Tortonian erosion in the Folded Molasse belt, but also a change in flexural geometry of the basin shape which is as yet poorly understood.

Also the subjectively generalized onlap pattern (Fig. 4) reflects a significant but rather gradual difference between both Molasse megasequences. An older rate of 2.5 $cma^{-1}$ is replaced in Rupelian time (33 Ma) by the much slower rates of 0.3 to 0.6 $cma^{-1}$. Poorly controlled onlap during the younger Molasse megasequence appears nearly stationary. Averaged over the entire basin and the total fill, the onlap rates vary between 0.3 and 0.6 $cma^{-1}$.

## LITHOSPHERIC FLEXURE

The base of the Molasse sequence dips southward at angles increasing from 1.5° to 6° and averaging 3° (Fig. 7). Dips of the less well known Moho are steeper but roughly conformable to the

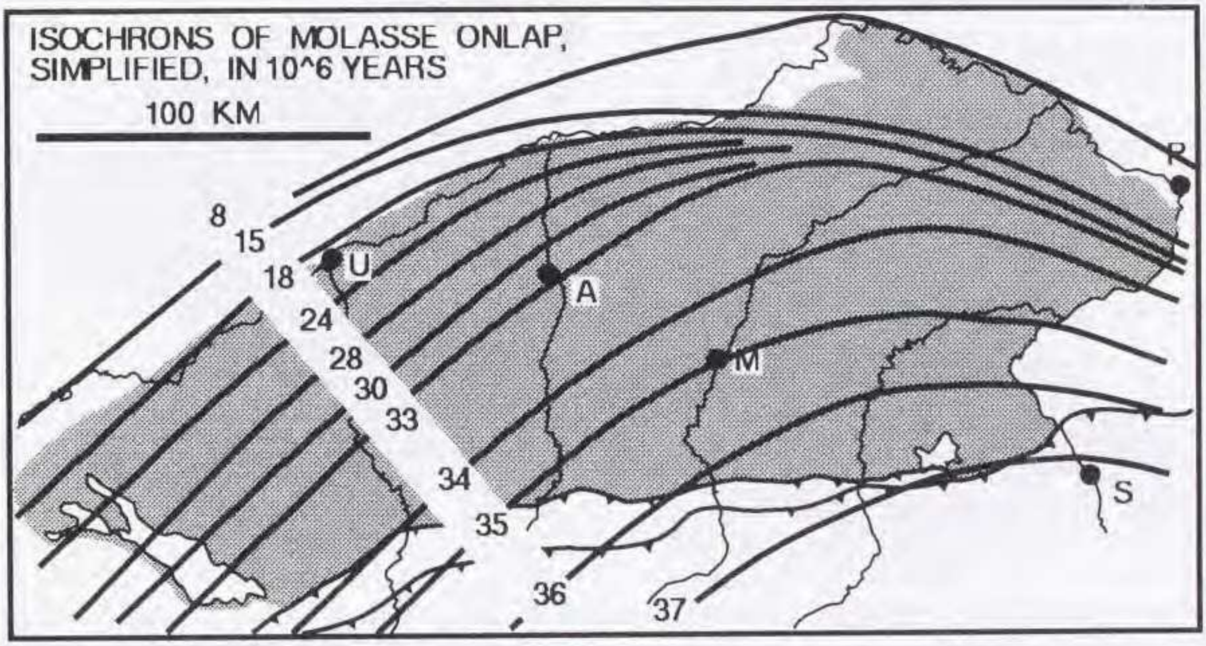


FIG. 4. Onlap map of German Molasse Basin (shaded), drawn by generalizing the onlap map of Fig. 3. Contours: lines of equal time of zero deposition. Numbers: ages in Ma.

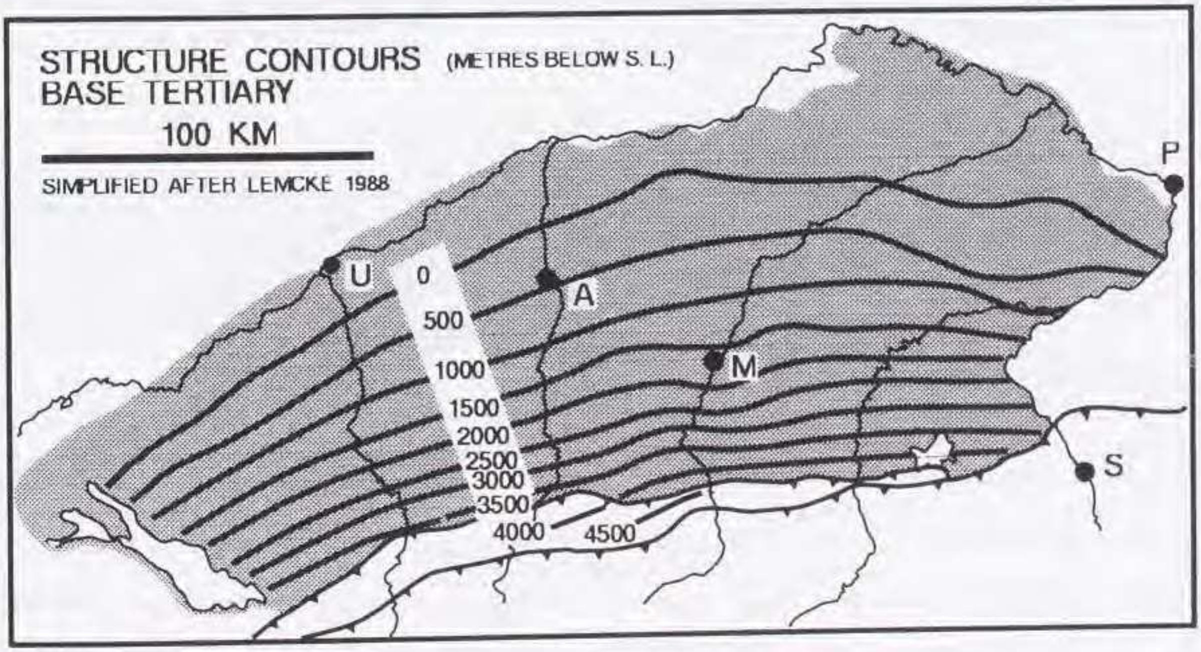


FIG. 5 German Molasse Basin (shaded), structure contour map of base Molasse in meters subsea, after Lemcke (1988).

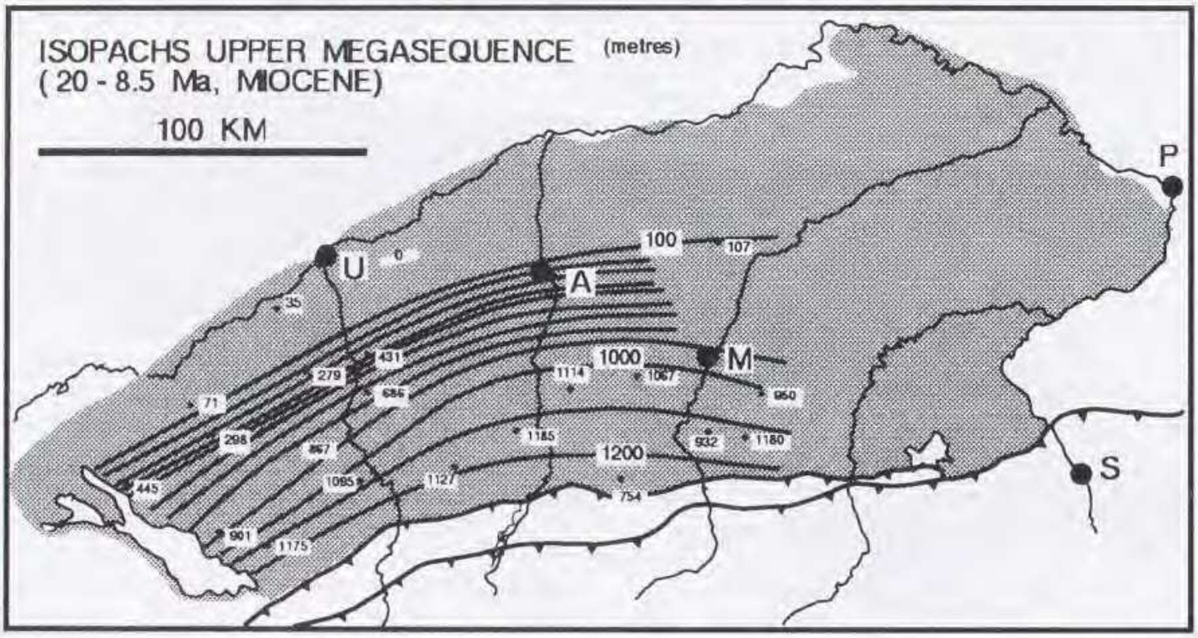


FIG. 6. German Molasse Basin (shaded), isopachs (in meters) of the Molasse Upper Megasequence as defined on Figure 2. Contoured interval is based on assorted well data shown as number fields.

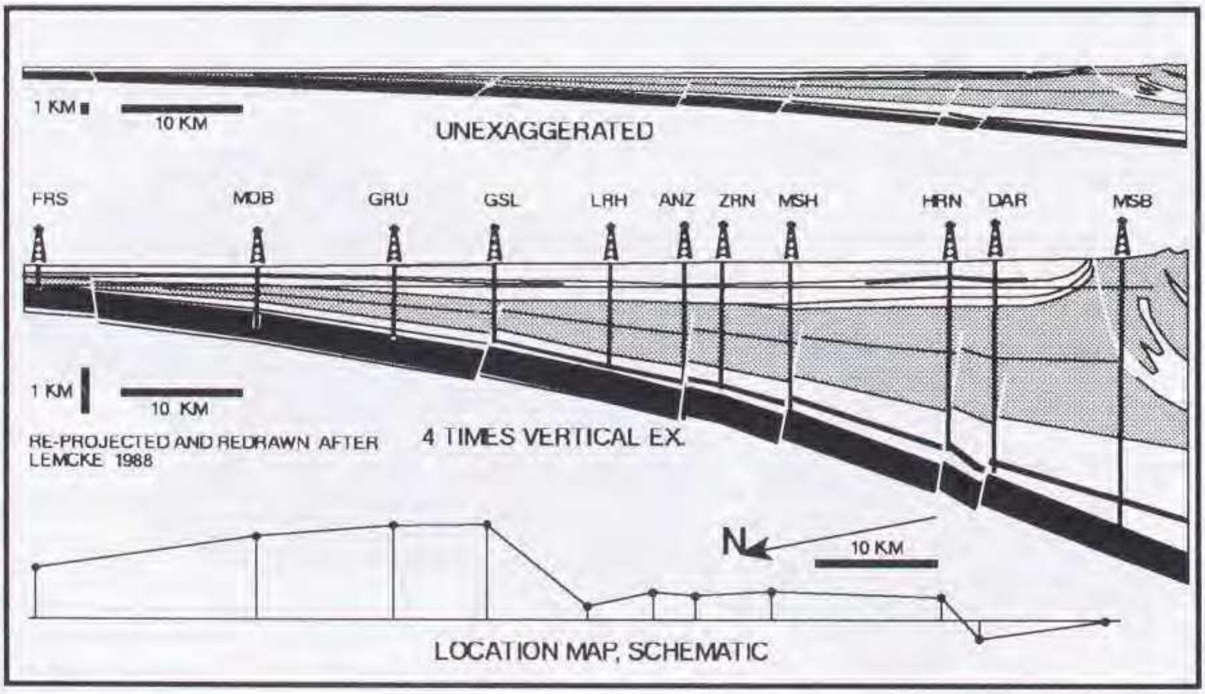


FIG. 7. Structural cross-section of German Molasse Basin based on well data, re-projected, restored to 1/1 vertical exaggeration, and redrawn after Lemcke (1988). Black: Malm carbonate of foreland series. Higher back line: Priabonian transgressive shales. Shaded: Chattian and Aquitanian interval. Groups of letters identify wells.

Molasse base (Müller et al., 1980; Giese et al., 1982; Prodehl and Aichroth, 1992). This crustal structure is interpreted as caused by elastic flexure of the lithosphere, loaded first by the Mesozoic passive-margin series, and later by subduction and by the topographic load of the Alps (Roeder, 1980; Royden and Karner, 1984).

Some of the studies of the European crust and its cumulative load have encountered unsolved mismatches and problems (Lyon-Caen and Molnar, 1989), partly ascribed to its complex origin, and partly to the mantle-induced rise of the Rhenish Massif. Therefore, we have limited present modelling efforts to an assumed flexural wavelength of 200 km, to an implied lithospheric elastic thickness of 29 km, and to an implied flexural rigidity D of $7 \cdot 10^{23}$ Nm. Although these values avoid the known mismatches, they are consistent with a European crust weakened by polyphase tectonics of Mesozoic and Tertiary age, and they can be matched by extrapolating southward the geometry of the Molasse Basin and its substratum (Figs. 5 to 7).

### Normal-Faulted Molasse Basin Slope

Normal faults with throws of up to 0.2 km affect most of the German Molasse Basin and form oil and gas traps (Lemcke, 1988). These faults are of Oligocene to end-Aquitanian age, and they display a northward synsedimentary migration (Fig. 8). In the west part of the German Molasse Basin, an additional younger generation of normal faults is of lower to middle Miocene age (Lemcke, 1988).

A numerical estimate based on the geometry of circular bending (see Appendix) shows that the earlier faulting is consistent with an elastic deflection of a 20 km thick brittle upper crust with a neutral fiber at its base. In a 20 km long dip segment of the Molasse Basin floor, about 1 fault per km with a displacement of about 0.1 km would accommodate the brittle strain of elastic-load flexure.

Normal faults of the younger generation continue the outward migration of flexure, but during an interval without enough documented elastic-load flexure of Alpine origin (see Appendix). Therefore, some of these faults are perhaps related to a non-Alpine component of extensional uplift in the Rhenish Massif as defined numerically (Karner and Watts, 1983; Lemcke, 1988; Lyon-Caen and Molnar, 1989), or to the uplift of the Vosges-Black Forest Arch (Ziegler, 1994).

## MEASURING SYNDEPOSITIONAL MOVEMENTS

Formation and filling of the Molasse foredeep took place during unknown amounts of crustal shortening along its south edge. To estimate the Alpine frontal strain, we must review all of its components. Following Means (1976), we define strain as the normalized change in length, and we define bulk strain as shortening or thrust overlap, measured as a distance. For the purpose of the present paper, convergence rate is bulk strain per unit time, plate convergence is Eulerian motion measured as a bulk strain along a defined small circle, and plate convergence rate is Eulerian bulk strain per unit time.

The zero edge of Molasse deposition advances (onlaps) northward relative to the basin floor. Although this onlap is largely independent of the Alpine strain, both are geologically related and therefore should be compared. Our study of Alpine-related basin progradation is illustrated by charts of the Molasse onlap (Figs. 3 and 4), by a chart of convergence rates and distances through time (Fig. 9), and by the restoration of one of our cross sections (Encl. 4).

The Northern Alpine front has advanced relative to undislocated or "pinned" (Boyer and Elliott, 1982) Molasse Basin fill. Trans-Alpine compression implies that the northern and southern Alpine fronts have approached one another. The trans-Alpine plate convergence has been traced through time by mapping the Atlantic sea floor anomalies and by Eulerian vector addition (Le Pichon et al., 1973; Dewey et al., 1973; 1989; Roeder, 1989). This data set is independent of Alpine data and quantifies both trans-Alpine plate convergence and convergence rates.

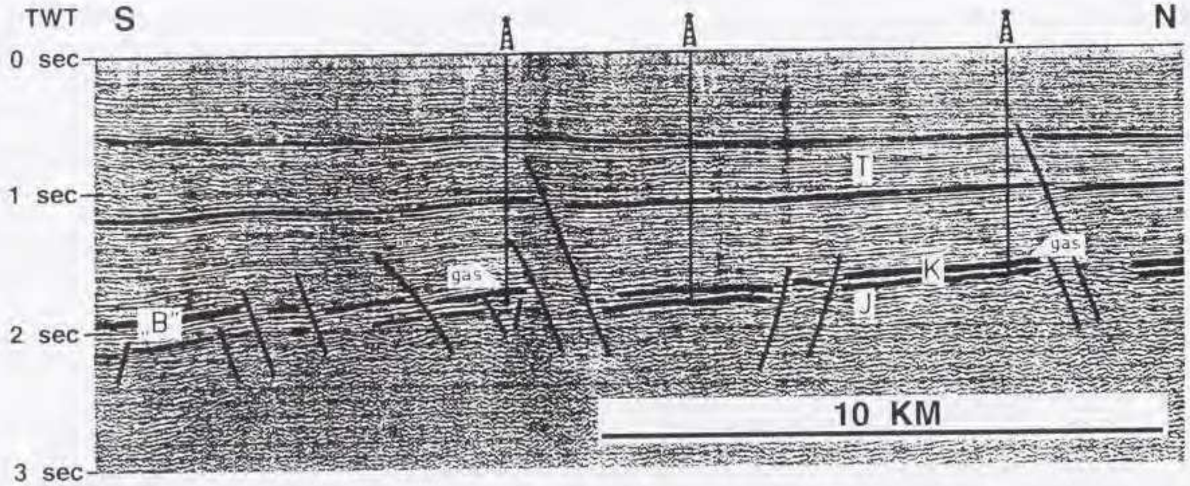


FIG. 8. Seismic dip line from the Undisturbed Molasse, east of Munich (after Bachmann et al., 1982), showing extensional normal faults, synthetic and antithetic to the southern regional dip and their successively younger synsedimentary activity from S to N.

To describe the bulk strain of the Molasse Basin, the difference must be established between plate convergence, South-Alpine convergence, and trans-Alpine convergence. Since tectonic events reach varying rates on either Alpine flank, the movements must be traced through time, by using literature data of vastly different resolution.

## Convergence Data

In Figure 9 we have compiled Alpine convergence data through time since the trans-Alpine or Europe-Africa collision of latest Eocene age (38 Ma). The data are compiled from the review literature quoted in the following text segments. The vertical axis is in Ma shown as numbers at the left edge. The horizontal dimension of the five plots given is in km of convergence shown to the right of the plots. Uncertainty or ranges are expressed in shades of grey.

The output of this diagram is the plot to the right. It has been obtained by linearly subtracting from the trans-Alpine plot, the inner-Alpine convergence, the South-Alpine convergence, and the Orobic convergence. The North-Alpine convergence, therefore, is a best collective estimate.

The trans-Alpine plate convergence (38 to 0 Ma) has been determined by adding the vectors across the boundaries of the European, Adriatic, Maghrebian, and African plates (Roeder, 1989; Roeder and Scandone, 1992). The convergence shown is a vector describing the movement between Verona and Munich. Depending on the choice of Atlantic-derived data, the convergence amounts to 610 km since collision, and the rates vary between 1 cm/a and 2.2 cm/a, with an overall average of 1.4 cm/a. The rate increase since 9 Ma is an effect of the change in the Europe-Africa vector (Dewey et al., 1989).

South-Alpine bulk strain of Neogene age is shown to vary between 55 km (Schönborn, 1992) and 115 km (Roeder, 1992). Both quantities are speculative. Pulses in South-Alpine strain rates, based on stratigraphic data (Scandone et al., 1989) and radiochronologic data (Schmid et al., 1987) are shown in the chart, but are too detailed to be of much use in the Molasse Basin. An earlier South-Alpine event is identified as Orobic, and its bulk strain of 50 km is very uncertain.

Combined Intra-Alpine and North-Alpine bulk strains of Neo-Alpine age (Oligocene to post-middle Miocene, Trümpy, 1980) are widespread, polyphase, and accompanied by a crustal shortening estimated at about 110 km in the Swiss segment (Trümpy, 1980; Pfiffner, 1992; Ziegler et al.,

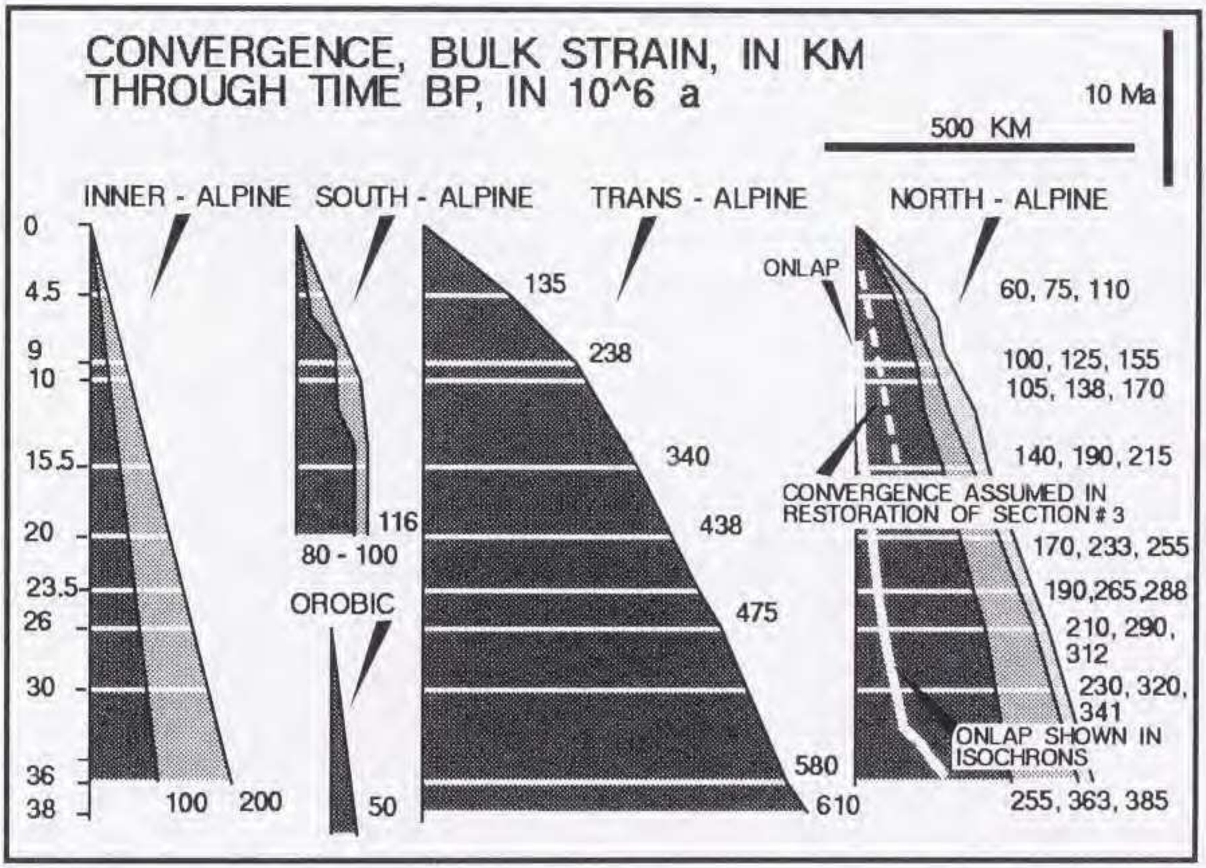


FIG. 9. Binomial Convergence-Bulk strain diagrams. Vertical: time axis in Ma. Horizontal: distance axis in kilometres.The diagrams show literature estimates of Alpine convergent bulk strain and their evolution through Oligocene and Neogene time. Dark and light shading: lower and higher amounts of convergence. Solid white line: onlap pattern shown in Figs. 2 and 3. Dotted white line: convergence used in retro-deformation on Encl.3.

this volume). For lack of more precise data, we have applied the Swiss shortening to a strain balance of the German Molasse Basin.

In the North-Alpine column of Fig. 9, we have added a strain path (white dots) of a tectonic restoration (see Encl. 4) which ignores the compilation almost completely. This reflects a lack of confidence in the compiled data, as well as in the North-Alpine subsurface structure, but not in the basic philosophy of strain compilation.

In Fig. 9 we have also added the rate of sedimentary onlap in the German Molasse Basin (white line) obtained by quantifying Fig. 4.

## STRUCTURE OF THE NORTH-ALPINE FRONT

The North-Alpine front is a convergent plate boundary. Its constituent tectono-stratigraphic units have been pre-deformed, assembled, and juxtaposed at different times and places. This implies that its structure cannot be balanced, and that some of its key aspects are unknown. However, an abundance of high-quality data is available. A small part has been used to illustrate the Alpine north front in four regional cross-sections running through the key wells of Vorderriss, Staffelsee, Hindelang, and Immenstadt (Encls. 1 and 2). All cross-sections show the stacked structural units and part of their uncertainties.

## Folded Molasse Unit

Müller (1970, 1978) used well control and vintage analog/single-fold seismic data to show that in many cross-sections of the Folded Molasse, the size of the synformal thrust slices is too small to fit into the space provided by the foredeep bottom. He inferred a detached and allochthonous fold belt overlying an overridden southward continuation of the Undeformed Molasse. In Fig. 10, this concept is applied to the Immenstadt area. The timing and amount of detachment at the base of the fold belt constitute significant solutions to problems of petroleum exploration along the Alpine north front.

A triangle zone along the north front of the Folded Molasse belt is documented by its north-dipping steep zone with a north-dipping backthrust implied at its base (Fig. 10). It serves as a merging termination or upper detachment to one or several blind south-dipping thrusts (Müller et al., 1988). The setting implies that the blind imbrication is coeval with the upturning of the monocline, that is, post-Tortonian (7 Ma). Further east, however, in the Perwang area of Western Austria (Janoschek, 1961; Tollmann, 1966), frontal imbrication is perhaps terminated not by an upper detachment, but by an erosional unconformity of mid- Aquitanian age (20 Ma). This interpretation would confirm the structural significance of the sequence-stratigraphic boundary at the 20 Ma-mark (P.A. Ziegler, personal communication).

In the western area, crossed by regional cross-sections 3 and 4 (Encl. 1), there is stratigraphic near-continuity between the steep zone and the adjacent syncline. However, there is a major thrust-type offset in a tight anticline near the middle of the folded Molasse zone. This vertical stratigraphic offset, typically of 3 to 4 km, separates an external Molasse unit and an internal Molasse unit, but the separating fault has not yet been traced regionally. In cross section 4, this thrust underlies four mapped Molasse folds, but its subsurface location is uncertain. Seismic data show the buried imbrication beneath the external Molasse unit (Fig. 10, Custodis and Lohr, 1974; Müller et al., 1988).

Cross-sections 3 and 4 (Encl. 1) intersect at the Immenstadt-1 well but show two contrasting interpretations of the subsurface architecture. Both versions are partly consistent with, but not clearly supported by, existing seismic data (Custodis and Lohr, 1974; Breyer, 1958). Both versions explain why the Immenstadt-1 well did not encounter the Chattian Baustein formation.

In cross-section 3 (Encl. 1), consistent with the classical imbrication model (Ganss and Schmidt-Thomé, 1955), the sole thrust of the Internal Molasse Unit passes below the bottom of Immenstadt-1. In cross-section 4, illustrating the newer concept by Müller (1970, 1978), the sole thrust of the Folded Molasse belt is cut by the well and overlays a parautochthonous Molasse unit. Both interpretations are further complicated by a low-angle backthrust merging with the upper detachment of the triangle zone.

Of the two interpretations, the version given in cross-section 4 suggests, but does not prove, a stratigraphic contact between fully allochthonous Helveticum and Molasse, later dislocated together with the Helveticum. The alternate interpretation (cross-section 3) shows only an uncritical thrust contact between Molasse and Helveticum. At present we prefer the version shown in cross-section 4, because of its regional suitability, and because of its ability to explain the juxtaposition of Molasse and Helveticum.

## Helveticum Units

This group of one or more thrust sheets is located south of the Molasse unit. It is composed of an Oxfordian to Eocene shale-carbonate series, and it is interpreted as a detached part of the Mesozoic passive-margin series and pre-Oligocene Molasse Basin fill. Only a small part of this unit is present in outcrop. In our cross-sections it forms a steep-flanked, tight, and faulted antiform of thrust units. On its north flank, the antiform is overlain by Molasse and on its south flank by the Rheno-Danubian flysch unit. Basin geometry and sparse well data suggest that the Helveticum overlays

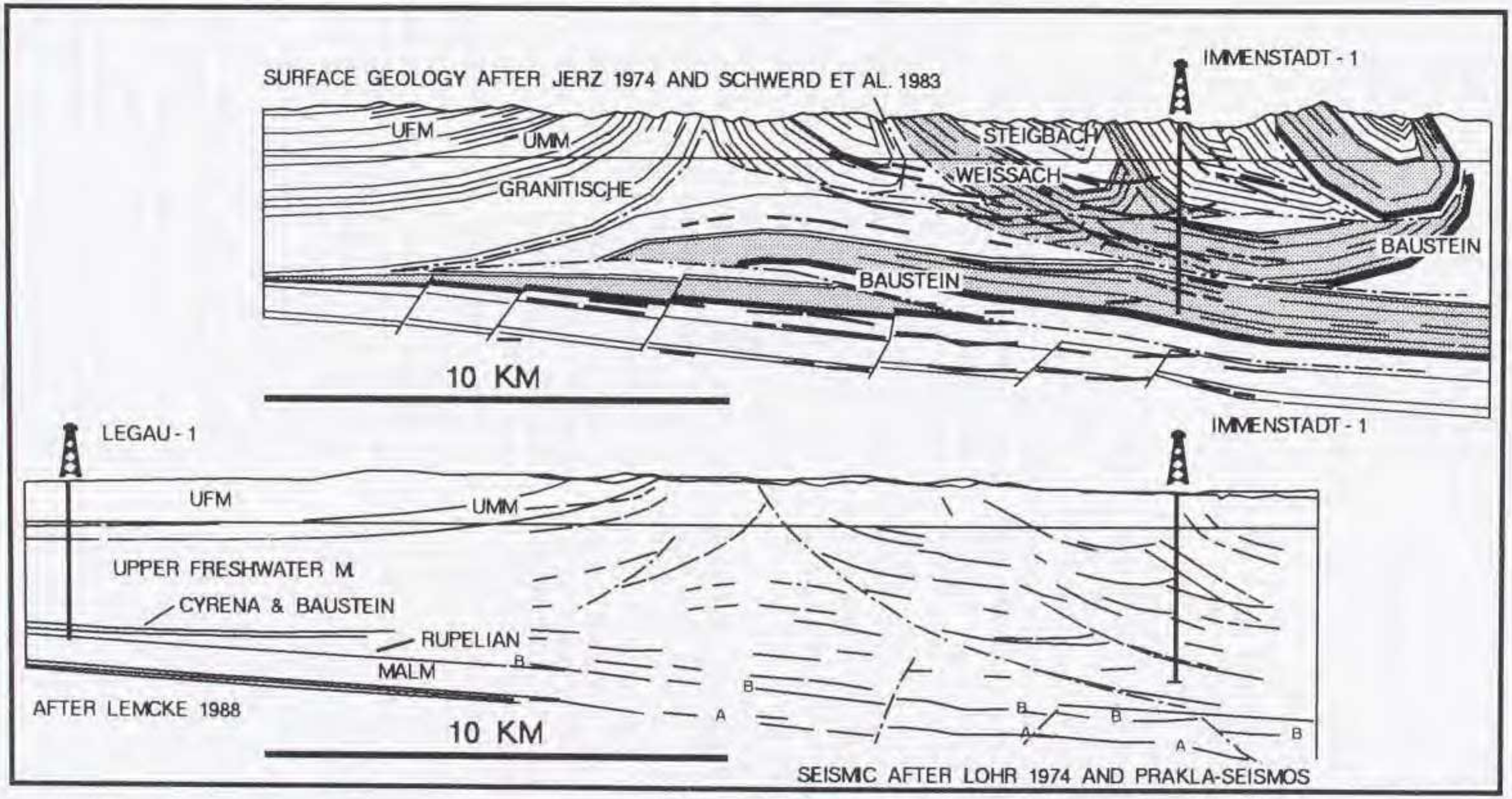


FIG. 10. Structural cross-section of Folded Molasse belt near town and well Immenstadt, juxtaposed with early analog and depth-converted seismic data. Seismic data from Breyer (1958) and Custodis and Lohr (1974). Geological data from Lemcke (1988) and obtained by construction based on surface data by Jerz (1974) and Schwerd (1983). Shaded: Weissach formation of early Chattian age (30 to 28 Ma). Black: Baustein formation of Rupelian/early Chattian age (31 to 28 Ma.) Seismic horizon A is interpreted as near top crystalline basement. Seismic horizon B is identified as near top Mesozoic carbonates.

unexplored and petroleum-prospective subthrust units of the Molasse which are within reach of the drill.
The top of the Helveticum is exposed on the steep to overturned north-flank of the antiform, where Molasse is overlying Helveticum with a minor hiatus and near-concordance, but the contact is a major and polyphase thrust fault wherever exposed. In several places (Encl. 1, cross-section 2), the top of the Helveticum appears in a tight antiformal window surrounded by flysch.

The main body of the Helveticum is known through four wells. The Kierwang-1 well (Encl. 1, cross-section 4) encountered undeformed Helveticum with an inferred thickness of 2.2 km (Müller, 1985). In the Vorderriss-1 well (Encl. 1, cross-section 1), the top 67 m of a strongly deformed Helveticum were opened (Bachmann and Müller, 1981). The Maderhalm-1 and the Hindelang-1 wells (Encl. 1, cross-sections 3 and 4) were spudded into large centres of polyphase folding and thrust imbrication (Huber and Schwerd, 1995). In outcrop, the width of the Helveticum decreases from a 10 km wide fold-thrust belt at the Rhine river to a quarry-sized sliver of indistinct shallow-water shale in eastern Bavaria.

The base of the Helveticum is a thrust fault with Molasse in the footwall, regionally mapped in Switzerland and western Austria (Trümpy, 1980) and encountered in the deep well Hindelang-1. We interpret this fault as part of the polyphase detachment separating the Folded Molasse unit from the overridden or parautochthonous Molasse (Müller, 1970, 1978). In many places, however, it is secondarily exposed by polyphase re-thrusting (Encl. 1, cross-sections 1, 3 and 4).

## Flysch Unit: Subalpine, Ultra-Helvetic, Rheno-Danubian Units

Sediments attributed to this tectonostratigraphic unit are present beneath a large part of the Northern Alps and range in age from Early Cretaceous to Eocene. Several thrust sheets are distinguished (reviews by Gwinner, 1978; Doben, 1981). In the present paper, the Flysch unit is an internally featureless, 1 to 2 km thick, allochthonous body. Additional detached flysch bodies are known in the footwall of the Helveticum and have been drilled in Hindelang-1 (Müller et al., 1992). Geodynamically, the North-Alpine flysch may represent the accretionary wedge of the Austro-Alpine trench innerwall. Its base, therefore, is a major branch of the trans-Alpine collision suture.

## Austro-Alpine Unit

This major tectono-stratigraphic complex is a nappe and clearly a detached part of a polyphase fold-thrust belt (Tollmann, 1976; Wessely, 1988; Roeder, 1989; Eisbacher et al., 1992). Its internal structure (Encl. 1, cross-sections 1 to 3) is not essential to the structure of the North-Alpine front. However, the depth, structure, and cutoff geometry of its base define the limits of the prospective subthrust province of the North-Alpine front.

The Austro-Alpine terrane involves a 3 to 4 km thick, extensional-margin series of Triassic to Cretaceous and, locally, to Eocene age. It underwent compressional and/or other tectonics above the Tethyan subduction during Late Cretaceous to Eocene times. Structural details show (Encls. 2 and 3, cross-sections 1-4) display a kinematic succession of detached folding, thrust faulting, and fault-bend folding. However, extensional structures of Jurassic age and facies changes of mid-Triassic age add severe complications to the thrust-fold evolution.

The base of the Austro-Alpine terrane is a thrust fault with a ramp-flat succession climbing northward through detached crystalline basement and through the sedimentary series. Over a large area, the Austro-Alpine sole fault is located within the mid-Triassic Raibl evaporite.

There are not enough data to constrain the ramp-flat sequence of this sole fault, but enough for an estimate of the finite ramp angle. The Austro-Alpine terrane has a dip width of 50 km and an estimated gross strain of 100%. The sole fault ramps up through 3 km of basement and 3 km of sediments. This suggests a finite ramp angle of 3.4°, if its origin predates the stacking of thrust sheets, and of less than 7° at the base of a stack. The second of these values is reasonable.

The depth to the Austro-Alpine sole fault is constrained by a major synform within the stack of thrust sheets near the Inn valley, by the Vorderriss-1 and several Austrian wells, by its re-emergence at the edges of the Tauern window south of the area studied, and by its up-plunge emergence at the Rhine valley. Seismological efforts to map its depth have not yet been very successful (Zimmer and Wessely, this volume).

## RETRO-DEFORMATION

Ideally, the Alpine tectonic evolution should be retro-deformed through the entire time interval of foredeep deposition. This has been done conceptually and graphically (Trümpy, 1980; Ziegler, 1987; Roeder, 1989), but quantitatively and at present, this is possible only if an Alpine strain path is assumed. We have illustrated (Fig. 9) the wide range of uncertainty in the Alpine convergent strain path (see also Ziegler et al., this volume).

As an alternative project with limited scope, we have retro-deformed the Molasse and Helveticum parts of cross-section 4 of Encl. 1 in four kinematic steps to the undeformed state of the basal Molasse and its substratum of Helveticum (Encl. 4). We have used the SNIP routine (Roeder, 1991) which is a computer-aided form of hand balancing. It is not as precise as commercial balancing software, but it can be used more easily in areas with poor data control.

If we assume that the documented 60 km of bulk strain represents an arbitrary 50% of the North-Alpine convergence (Fig. 9), we obtain a finite North-Alpine convergence rate of 0.59 $cma^{-1}$. Applied to the 60 km of bulk strain, this rate would date the retro-deformation series as early Messinian time (10.5 Ma) to the present. This implies that the entire Folded Molasse and most of the Undeformed Molasse strata are pre-kinematic with respect to the structures within the Molasse belt. This is consistent with the opinion of most workers (Doben and Frank, 1983; Schwerd and Unger, 1981; Schmidt-Thomé, 1962; Lemcke, 1988). In the following comments, reference to geological ages of kinematic events are based on this assumed strain path.

### Present State

If the convergence across the North-Alpine front has been decreasing, the present state may have been achieved up to 2 Ma before the present.

The Folded Molasse belt shows a detached Internal unit, a pinned External unit and a parautochthonous foreland with two footwall imbrications. The Helveticum terrane and the Internal Molasse unit have been jointly emplaced on a common sole fault. There is blind thrusting and complex interference between the backthrust front of the External unit and the allochthonous unit. The front of the Helveticum is a tight north-vergent antiform involving a stack of thrust sheets. The steep, north front of this antiform contains a strongly faulted depositional surface of Molasse on Helveticum.

### First Restorative Step

At a steady bulk strain rate of 0.59 $cma^{-1}$, the state shown here would date at 3.1 Ma or early Plaisancian. As determined by SNIP graphics, the bulk strain restored in this step is 6.2 km.

The frontal footwall imbrication is restored. This results in the unfolding of the present steep zone and the adjacent syncline. It also results in a restoration of the discordant low-angle backthrust. The sole fault, common to the Helveticum and the Internal Molasse unit, ends blindly beneath the External Molasse and the undeformed foreland. The imbricate structure of the Internal Molasse unit is fortuitously located in front of the internal footwall imbrication.

### Second Restorative Step

At a steady bulk strain rate of 0.59 $cma^{-1}$, the state shown would date at 4 Ma or early Pliocene. The SNIP-determined interval bulk strain is 5.3 km.

The Helveticum, probably overlying a carpet of involute sub-Alpine flysch, is shown as pushing an imbricate series of Oligocene and lower Miocene Molasse over a foreland series which includes beds as young as lower Chattian. At the front, this thrust is blind and ends at a northward migrating ("backpeeling") backthrust and steep zone.

### Third Restorative Step

At the model bulk strain rate of 0.59 $cma^{-1}$, the northward advancing front of Alpine compression would have reached the south edge of the presently preserved Molasse terrane at 9.7 Ma or early Tortonian. The SNIP-determined interval bulk strain is 33.8 km.

All frontal imbrications of the Internal Molasse unit are restored and placed south of the foreland Molasse. At the present contact between Molasse and Helveticum, the tight fold is restored, but none of the fault displacement affecting the contact. The hinterland of the Molasse terrane consists of Helveticum with its tectonic cover of Flysch and Austro-Alpine terranes.

At this stage, the hinterland of the Molasse is still overlapping the foreland Mesozoic series, by transport on the Helveticum sole thrust which is older than the third restorative stage. The amount of overlap is unknown. It can be determined structurally (see Encl. 1, sections 1 and 2) or by applying a strain rate.

The Helveticum sole thrust may have started to break through the Molasse series to the surface, or it may have started the blind system with steep zone, backthrust, and "peelback" mechanism. The thickness of the southernmost, still undisturbed Molasse series is graphically estimated at 6.5 km.

### Fourth Restorative Step

Displayed at a scale change (Encl. 4, cross-sections 5 and 6 ), this step contains a retro-deformation of the Helveticum terrane and a retro-displacement to its position downdip of the foreland Mesozoic series. Both steps are highly speculative. As modeled graphically with the SNIP routine (Roeder, 1991), this step comprises an interval bulk strain of 54.7 km. As part of this strain, the internal deformation of the Helveticum terrane has been graphically estimated at 56%, based on its documented style (Encl. 2, cross-section 4).

### Tectonic Chronology

The timing of the tectonic events modeled is very uncertain; however, it is a key element in judging the availability of thrust-buried maturation of hydrocarbon source-rocks.

Retro-deformed cross-section 6 (Encl. 4) shows a concept of the basin state at the time when the Molasse fold-and-thrust belt began to form. The entire Molasse series is shown to overlap unconformably an imbrication of flysch and Austro-Alpine nappes. The basin is shown to open towards the south. At a realistic basin-bottom slope of 3°, the not yet deformed Molasse Basin extended another 60 to 80 km to the south. The stack of Flysch and Austro-Alpine nappes, we assume in this model, had been assembled and emplaced prior to the deposition of the oldest Molasse of late Eocene age. Therefore, this model implies that the North-Alpine front was tectonically relatively quiescent during Priabonian (36 Ma) to Eggenburgian times (19 Ma).

This very long quiescence is not consistent with the trans-Alpine convergence data. Therefore, it is more likely that the site of emplacement of Flysch (piggy-backing the Austro-Alpine) over its foreland of Helveticum had been located 60 to 80 km south of where it is shown in the reconstruction. The restoration shown suggests, however, that detachment of the Helveticum commenced at the beginning of the younger megacycle during the early Miocene.

The long tectonic quiescence could also be avoided by assuming much lower strain rates (Ziegler et al., this volume). However, fold-and-thrust belt tectonics (Bally et al., 1966; Boyer and Elliott, 1982; Price and Hatcher, 1983; Suppe, 1985; Roeder, 1992) tend to support the higher strain rates assumed in our model.

The structure sections, convergence rates, and retro-deformations shown in the present paper illustrate, rather than solve the problems. New work focussed on the tectonic chronology is needed to arrive at reliable, or at least internally consistent, results.

## PETROLEUM RESOURCES

The German segment of the Molasse Basin is in a mature state of petroleum exploration, and production has been declining since a decade. About 600 wells were drilled in this basin between 1948 and 1985. Based on cumulative production until 1994 (Niedersächsisches Geologisches Landesamt, 1994)), the total developed reserves, from 59 mostly small oil and gas fields, is estimated at $10 \cdot 10^6$ t ($80 \cdot 10^6$ bbl) of petroleum liquids and $21 \cdot 10^9$ $m^3$ of gas (735 BCF) with the peak of production attained between 1966 and 1974.

Since 1992, there has been little activity to ease the steep decline of production. In 1994, the remaining proven and probable reserves in the 25 fields still on stream were $0.5 \cdot 10^6$ t ($4 \cdot 10^6$ bbl) of oil and $10^9$ $m^3$ (35 BCF) of gas.

Figure 11 shows the basin-wide distribution of oil and gas fields. Their close relationship to Oligo-Miocene extensional fault blocks is evident. Filed names, detailed geology, and discovery histories are well summarized by Lemcke (1988).

Productive reservoir rocks (Lemcke, 1988) include Mesozoic carbonates of the Helveticum and the Molasse Basin floor, transgressive late Eocene sands, Oligocene Baustein coarse clastics, and various coarse clastic horizons within the Miocene Molasse.

Source rocks for oil and associated gas in the western basin parts, established with reasonable certainty, include the Toarcian Posidonia shales (Jurassic, 194-188 Ma) which provide the charge for Mesozoic and basal Tertiary reservoirs. The coals of the Permo-Carboniferous trough fill are near the high-temperature end of the gas window (Kettel and Herzog, 1989).

Source rocks for oil in Tertiary reservoirs of the eastern basin parts are Oligocene shales (Fisch Schiefer, 34-32 Ma). Biogenic (immature) gas in eastern Bavaria was generated in late-Oligocene and early- Miocene deeper marine shales (Schoell, 1977).

On a more speculative level, source-rock quality (Lemcke, 1988) is also ascribed to the Muschelkalk (Triassic, 240-230 Ma) and to the Helvetic Quintner Kalk (upper Malm, 150-145 Ma). In the southern region, thrust-loaded with Alpine units, any organic-rich formation of Jurassic to Oligocene age will potentially generate thermal gas, available for updip migration. Of particular interest in exploring sub-Alpine trends is the Oligocene Fisch Schiefer in subthrust position.

The western basinal region, where the dominant basin fill consists of Lower Freshwater Molasse, is barren and generally devoid of source-rocks and reservoir/seal pairs. However, in the north part of this region, there are Mesozoic reservoirs charged by Mesozoic source rocks.

### Remaining Hydrocarbon Potential

Presently developed production is limited to the undeformed part of the Molasse Basin. A significant percentage of the known and possible prospects has been drilled. Undiscovered reserves from the existing geological play types are judged to be small. Any renewed exploration would therefore depend on new or untested old play types.

New play types would have to focus on the most likely hydrocarbon kitchens in the southern parts of the basin which are tectonically buried beneath Alpine nappes. Any renewed interest would also have to focus on the updip migration pathways from these kitchens.

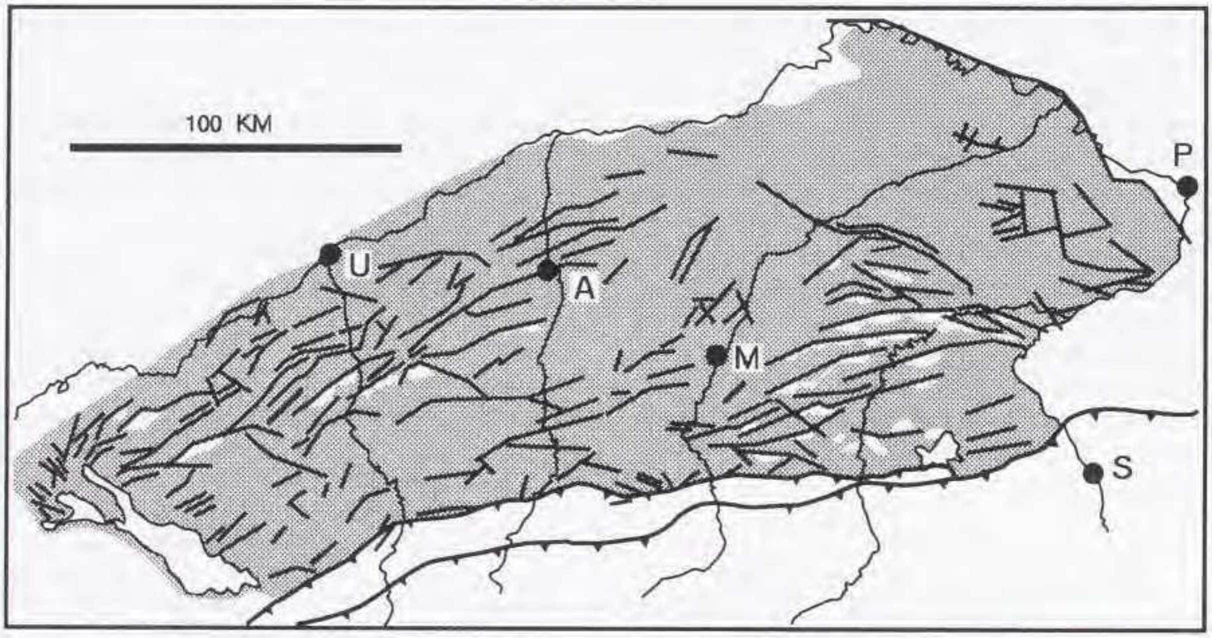


FIG. 11. German Molasse Basin (shaded) with simplified pattern of block faults and oil and gas fields (white), (after Lemcke, 1988).

The sub-Alpine hydrocarbon kitchens are poorly known. There are no publicly accessible data on source-rock volumes in the German Molasse Basin, nor in North-Alpine terranes. Applied to a basin volume of 80,000 $km^3$, the estimates of pooled oil and trapped gas suggest a net petroleum yield ratio of 125 tons of oil and $0.6 \cdot 10^6$ $m^3$ of gas per $km^3$ of total basin fill. These ratios are less than 10% of a range of yields for productive sedimentary basins world-wide.

This vague estimate can serve as a guide-line for exploratory decisions. An optimistic interpretation of the estimate would hold that in the German Molasse Basin, updip migration has been partially blocked by traps located downdip or south of the existing productive area. Alternatively one could assume that sizeable quantities of hydrocarbons have been lost to the surface, as suggested by Ziegler et al. (this volume) for the Swiss part of the Molasse Basin.

**New Play Types**

In the German segment, exploration of the Folded Molasse and Alpine fold-thrust belt took place more than a generation ago and prior to the availability of modern seismic techniques and structural theories. It generated a geological framework and a significant number of oil and gas shows from deep and needed, but perhaps poorly located wells. A modern consortial effort with federal German support has led to two world-class wildcat wells (Vorderriss-1 and Hindelang-1) and has added modern seismic data, hydrocarbon shows, and significant geological insight.

A new effort in the Folded Molasse and frontal Alpine area is presently departing from the existing data set with modern techniques, concepts, and comparative examples. The effort is focussing on mapping structural traps in sub-Alpine migration pathways. Most likely, traps in this position will be parautochthonous imbrications in front of, or just beneath, the North-Alpine front.

Such traps require good reflection-seismic definition, a convincing geological interpretation, and a reasonable thermo-structural history. Furthermore, they must be within reach of the drill, in topographically accessible locations, have a plausible charge mechanisms, and, all important, it must be demonstrate that they have an economically viable reserve potential.

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## APPENDIX: NORMAL FAULTS AND CURVATURE OF FLEXURE

Extension by bending depends on the difference in arc length. The outer circumference of an arc segment of a length of (pi)(alpha) and of a thickness (delta)h is longer than the inner arc segment by an amount of (delta)l:

(delta)l = (delta)h·(pi)(alpha)/180

The end-loaded elastic-load curve has its maximum deflection angle at its free end. At a flexural length of 160 km and a maximum deflection of 36 km, the first derivative of the elastic-load curve (achieved numerically with MathCAD) suggests a near-steady decrease in deflection of about 0.8 degrees every 10 km. An arc length of 21 km taken from the middle of the foreland crust has a curvature of 2.5 degrees. Its convex upper surface has an excess length of 0.85 km, if it is 20 km thick. This excess length could be accommodated by 17 normal faults each with 0.1 km of displacement.

## Enclosures

Encl. 1 Four regional structural cross-sections through North-Alpine front, compiled and constructed from data by Bachmann et al. (1982, 1987), Müller (1970, 1978, 1987), Müller et al. (1988), Doben and Frank (1983), Schwerd (1983), and Lemcke (1988). Hachure: detached crystalline foreland basement. Dark grey: Helveticum and foreland Mesozoic rocks. Mid-grey: silhouette of Austro-Alpine and Flysch units. Black: Baustein formation. Light grey: Chattian, Aquitanian, and (in sections 3 and 4): lower Chattian-age rocks.

Encl. 2 Structural details of cross-sections 1 and 2 shown in Encl. 1, based on referenced data sources and on Bachmann and Müller (1981), Huckriede and Jacobshagen (1958), Tollmann (1976), and field work by D. Roeder in 1995.

Encl. 3 Structural details of cross-sections 3 and 4 shown in Encl. 1, based on referenced data sources and on Bachmann and Müller (1981), Huckriede and Jacobshagen (1958), Tollmann (1976), and field work by D. Roeder in 1995.

Encl. 4 Retro-deformation in 5 stages of cross-section 3 of Encl. 1. Discussion in text.